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Visualizing three-dimensional configuration spaces for mechanical design

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Abstract

We describe a configuration space visualization program for mechanical design. Configuration space is a geometric representation of mechanical function that encodes quantitative information, such as part motions, and qualitative information, such as system failure modes. The program helps designers elucidate the qualitative information, which appears as geometric properties of the configuration space. The research challenge is to relate the configuration space geometry to the mechanical function of the parts. This is difficult because configuration space is a foreign language to designers and because its geometry is complex and nonlinear. We demonstrate the efficacy of our program on two small, but realistic design examples.

Keywords: computer-aided mechanical design, configuration space, contact analysis.
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1 Introduction

We are studying difficult geometric problems in computer-aided mechanical design where visualization plays a key role. Mechanical design is the task of creating a system of parts that performs a function reliably and economically. It is a ubiquitous activity that spans mechanical, electrical, and biomedical engineering. Some common systems are automobile transmissions, robot manipulators, micro-mechanisms, and prosthetic devices. Designers need to devise, analyze, and compare prototypes to produce optimal designs. Computer-aided design reduces design time and improves quality by shifting some of this activity from physical to electronic prototypes.

Our research addresses the fundamental design task of contact analysis. Contacts are the physical primitives that make mechanical systems out of collections of parts. Systems perform functions by transforming motions via part contacts. The shapes of the interacting parts impose constraints on their motions that largely determine the system function. Contact analysis is the task of deriving and analyzing these constraints. Designers use contact analysis to ensure correct function and to optimize performance.

We illustrate contact analysis on the film advance of a movie camera (Figure 1). The mechanism consists of a driver cam, a follower, and a film strip attached to a frame. The driver cam rotates counter-clockwise about a shaft on the frame, while the enclosing follower is attached to the frame by a pin joint. The film translates vertically in a plane orthogonal to the page. The part contacts determine the mechanical function of the system. The cam pushes the right side of the square follower profile, which moves the follower right until its tip engages the film. Next, it pushes the bottom of the square profile, which moves the tip down, which advances the film by one segment. Next, it pushes the left side of the profile, which disengages the follower tip from the film. Finally, it pushes the top of the profile, which raises the follower in preparation for the next cycle.

We have developed software that automates contact analysis via configuration space computation [4, 3]. Configuration space is a geometric representation of rigid-body interaction that encodes the requisite contact information for mechanical design. It encodes quantitative information, such as part motions, and qualitative information, such as system failure modes. The software computes configuration spaces for planar systems, which account for most mechanical design applications. It implements quantitative queries that support simulation, parametric design, tolerancing, and other design tasks.

In this paper, we present a configuration space visualization program. The goal is to elucidate qualitative contact information, which appears as geometric properties of configuration space. The research challenge is to relate the configuration space geometry to the mechanical function of the parts. This is difficult because configuration space is a foreign language to designers and because its geometry is complex and nonlinear. We demonstrate the efficacy of our program on two small, but realistic design examples. The examples show that standard visualization techniques suffice for some design tasks, while other tasks re-

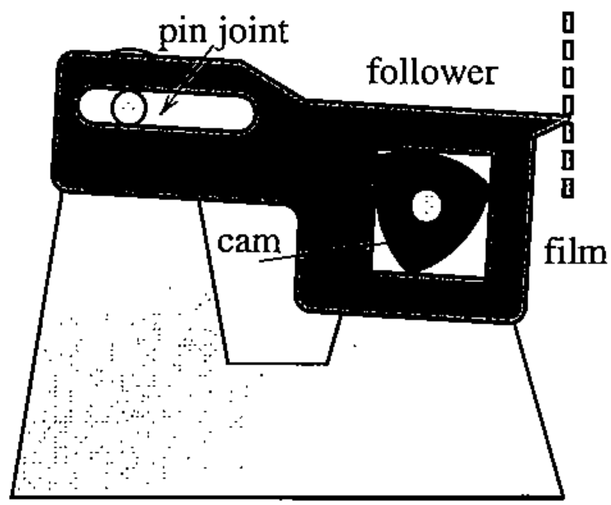


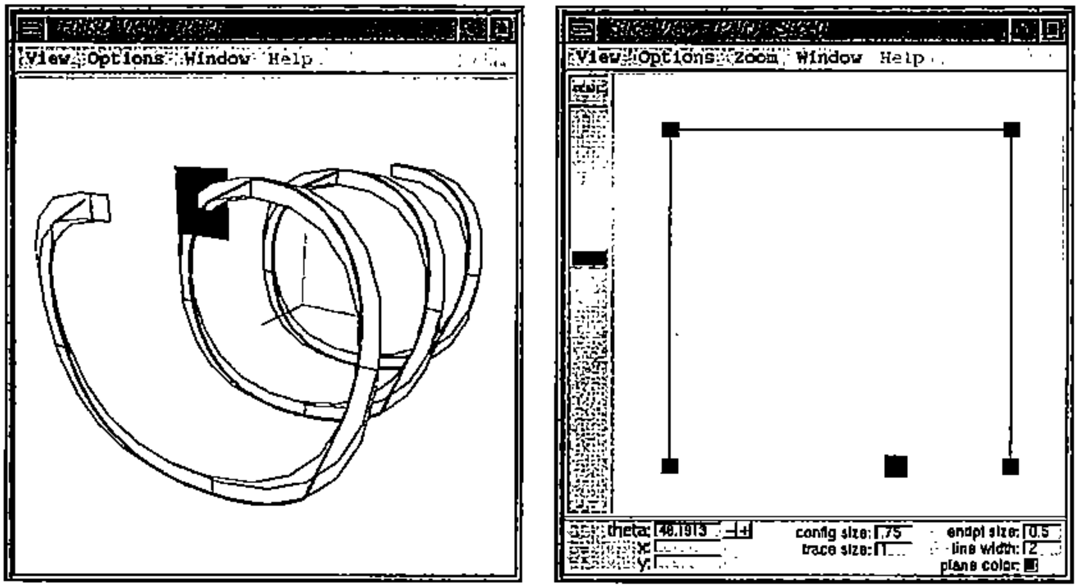
Figure 1: Film advance mechanism of a movie camera.

quire novel capabilities. Our aim is to alert the visualization community to this research opportunity and to foster an exchange of ideas.

2 Configuration space

Configuration space is a general representation for rigid part interaction that is widely used in robot motion planning [2]. We model the interactions of pairs of planar parts with three-dimensional configuration spaces whose points specify the spatial position (u, v) and orientation ψ of one part with respect to the other. Configuration space partitions into three disjoint sets that characterize part interaction: blocked space where the parts overlap, free space where they do not touch, and contact space where they touch without overlap. Blocked space represents unrealizable configurations, free space represents independent part motions, and contact space represents motion constraints due to part contacts. Free and blocked space are open sets whose common boundary is contact space.

Figure 2 shows our visualization of the configuration space of the cam/follower pair in the film advance. The (u, v) coordinates (the red and green axes) are the position of the cam center relative to the center of the enclosing follower slot and ψ (the blue axis) is the angle between the parts. The full view shows the contact space, which forms a narrow spiral channel whose interior is the free space and whose exterior is the blocked space. The contact space consists of algebraic patches that represent contacts between pairs of part features. For example, the yellow patch represents the contact between the bottom tip of the cam and the follower bottom, while the blue square on the patch marks the configuration shown in Figure 1. As the parts move, their configuration traces the curve shown in purple.



(a) (b)

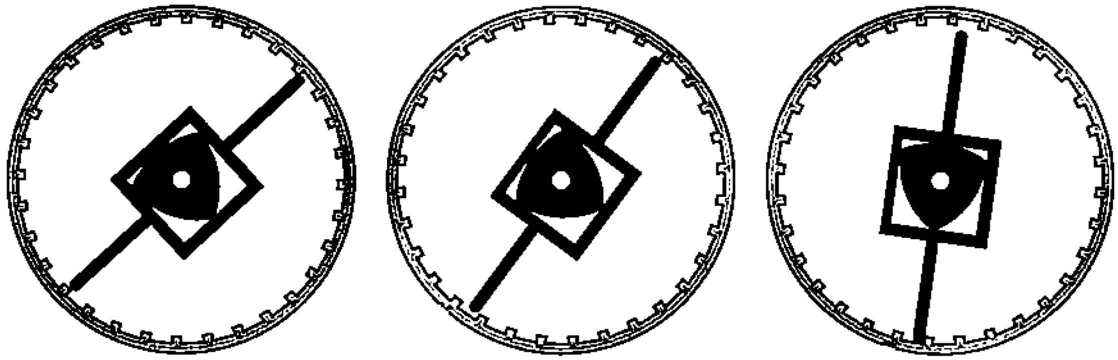
Figure 2: Driver/follower configuration space: (a) full view (b) typical cross-section.

The red cutting plane defines the cross-section shown in the two-dimensional view, which represents cam translation at a fixed orientation. The contact space is a square whose sides are the contact curves of the interacting features. For example, the yellow line corresponds to the yellow patch in the full view. The cross-section shows that the cam sides do *not* touch the follower, although they appear to touch in Figure 1. The free space is the interior of the square.

The visualization reveals the key qualitative property of the configuration space: the channel forms a spiral that spans the full range of cam orientations. The spiral shape implies that the follower moves right, down, left, and up. The full range implies that the cam rotates through the four stages without jamming. Narrowing the follower slot or widening the cam transforms the free space into a worm shape whose head and tail consist of jamming configurations beyond which the cam cannot proceed. The visualization also shows the quantitative aspects of the configuration space, such as the range of vertical follower travel, which must match the film spacing.

3 Visualization challenges

The cam/follower configuration space is simple enough that interactive viewing (rotation, zooming, coloring, shading) reveals its qualitative features. However, most designs involve configuration spaces that are too complex for this approach. We illustrate the problems



(a) (b) (c)

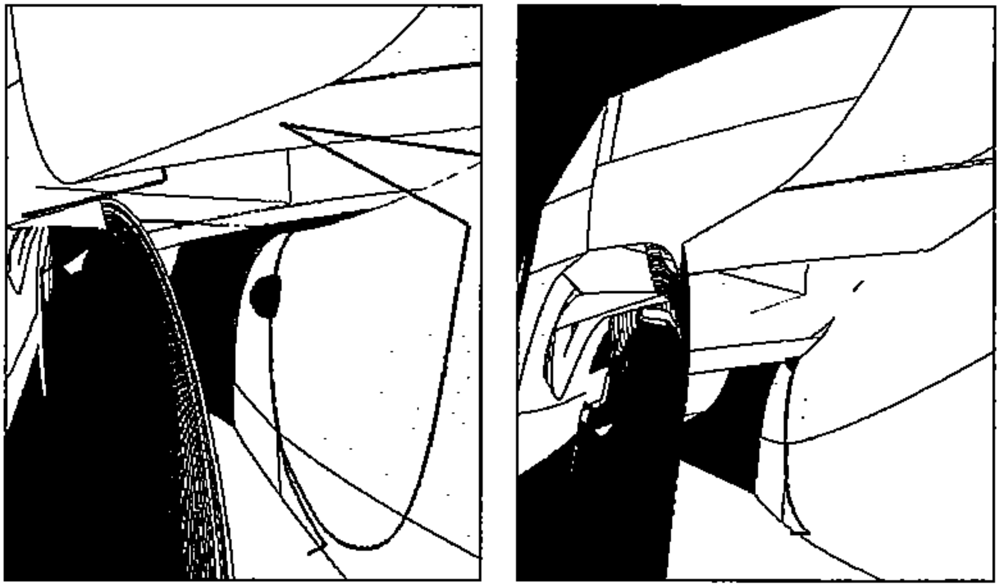
Figure 3: Intermittent gear mechanism: (a) upper follower pawl engaged, (b) follower disengaged, (c) lower pawl engaged.

with an intermittent gear mechanism (Figure 3). The mechanism consists of a cam, a follower with two pawls, and a gear with inner teeth. The cam and the gear are mounted on a fixed frame and rotate around their centers; the follower is free. Rotating the cam counter-clockwise causes the follower to rotate in step and to reciprocate along its length. The follower engages a gear tooth with one pawl (snapshot a), rotates the gear, disengages, rotates independently while the gear dwells (snapshot b), then engages the gear with its opposite pawl and repeats the cycle (snapshot c).

The mechanism function is determined by the cam/follower and gear/follower configuration spaces. The former is identical to the movie cam/follower space because the cams are identical and the followers have the same inner profiles, which is all that interacts with the cam. The challenge is to visualize the gear/follower configuration space. We need to understand the qualitative function, to test for failure modes, such as jamming, and to compute important quantities such as the per cycle angular rotation and dwell time of the gear.

Figure 4 shows the gear/follower configuration space. We have picked an optimal viewing angle and focused on the region that is relevant to the mechanical function, which is a tiny part of the full space. Yet the qualitative features are hard to see because of the complex geometry. It is difficult to see how the parts move, much less to ensure correct function. The figure illustrates this point by contrasting the configuration space of a correct pair with that of a faulty pair that jams because the gear teeth are too long.

One way to visualize a complex configuration space is with cross-sections. We alleviate their known limitations in representing spatial geometry with interactive section selection, with multiple sections, and with graphical links between the sections and the full view. We superimpose the part motion path on the sections to see the global motion. The portion of the motion path that is far from the slice orientation should be viewed with care because it represents different contacts. We alleviate this problem by synchronizing the cross-sections



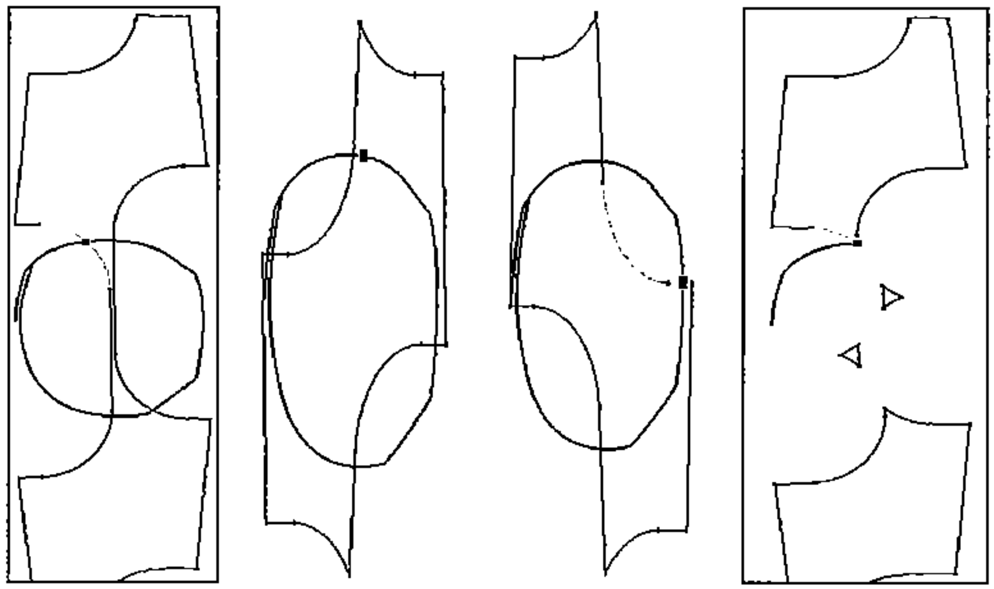
(a) (b)

Figure 4: Gear/follower configuration space: (a) correct; (b) faulty.

with an animation, but cannot illustrate that technique here.

The cross-section visualization program elucidates the gear/follower function. Figure 5a–c shows three cross-sections that correspond to the snapshots in Figure 3. In part a, the configuration is on the patch where the rounded tip of the upper pawl touches the side of the gear tooth and rotates it. The configuration follows the patch from left to right as the tip disengages then follows the vertical patch below as the pawl slides along the tooth top. (The curve changes as the dot moves; the combined effect is best viewed interactively.) In part b, the configuration has left the vertical patch and is moving right in free space as the opposite pawl approaches the gear. In part c, it reaches the green patch when the pawl tip engages the gear, traverses the patch as the tip pushes the gear, then reaches the displayed configuration on the yellow patch where the side of the pawl engages the gear.

Cross-sections a and d show the difference between the correct design and the faulty one with longer teeth. The parts are in the configurations of Figure 4. The faulty motion path is an open segment instead of a closed loop. It ends when the configuration reaches the right side of the yellow patch. The vertical channel is absent, which means that the pawl cannot slide along the tooth top because the other pawl has already hit an opposite tooth. We are developing interactive design software that allows us to discover that lengthening the teeth makes the channel grow narrower then vanish.



(a) (b) (c) (d)

Figure 5: Gear/follower configuration space cross-sections.

4 Conclusions

We have seen that configuration space visualization provides designers with important qualitative information about mechanical function. The outstanding problem is how to detect qualitative patterns in complex spaces. We conclude with a discussion of the longer term problems of higher dimensional spaces and specialized design tasks.

Some design tasks involve configuration spaces of higher dimensions. Pairs of spatial parts have six dimensional configuration spaces. Interactions among sets of parts, such as the intermittent gear system, occur in high-dimensional configuration spaces. A system configuration is free when no parts touch, is blocked when two parts overlap, and is in contact when two parts touch and no parts overlap. Direct visualization of these spaces is infeasible. We can visualize the configuration spaces of the interacting pairs, which are projections of the system configuration space, but it is difficult to determine the global topology from the projections. Intelligent projection techniques are needed to resolve this issue. The challenges are to find subspaces that reveal the relevant part interactions and to visualize them in a perspicuous way.

Specific design tasks pose their own visualization problems. Simulation raises the need to visualize part motions, which generate paths in configuration space. Our software can animate the parts while tracing the corresponding configurations in the pairwise configuration spaces. This technique also helps us probe the system configuration space topology without fully constructing it. Tolerance analysis raises the need to visualize parametric families of configuration spaces that represent the functional effects of manufacturing variations on part geometry [5]. These problems are prime candidates for interdisciplinary research in mechanical engineering and computer science.

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